

# The Second Law of Thermodynamics and Entropy-Decreasing Processes With $^4\text{He}$ Superflows

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**Abstract.** We review on a recently proposed quantum exception to the second law of thermodynamics. We emphasize that  $^4\text{He}$  superflows, like any other forms of flows, shall carry entropy or heat in a thermal environment. Following that, one can use a heterogeneous  $^4\text{He}$  superflow loop to realize entropy-decreasing processes. We also mention that the heat content of a superflow has an unusual dependence on flow velocity, which is an important factor contributing to the entropy-decreasing processes.

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The second law of thermodynamics (SLT) prohibits the decrease of the entropy in an isolated system. It rules out the desired possibility of utilizing the endless colossal thermal energy in the environment as the major energy source for the civilization. But is this SLT truly universal? We know that first law of thermodynamics is exact universal, because it is a manifestation of conservation of energy and quantum mechanics obeys the conservation of energy as a built-in law. Unlike the first law, SLT doesn't corresponds to a built-in rule in quantum mechanics. Imagine a situation in which that numberless physical processes obey SLT, but there is one quantum process which violates SLT, then in this situation we shall accept that SLT is not an exact law of nature and that there is an exception to SLT. It is quantum mechanics, rather than SLT, which is the true governing law of nature. In [1], we show that some  $^4\text{He}$ -superflow-involving quantum processes contradict SLT, and that it is possible to convert the thermal energy in the environment into useful energy. We shall review this quantum exception to SLT.

The entropy-decreasing quantum processes rely on a fundamental property of  $^4\text{He}$  superflows. Whether does a  $^4\text{He}$  superflow carry entropy or thermal energy? The phenomenological two-fluid model of superfluid  $^4\text{He}$  gives a no answer. But this is

at odds with quantum mechanics. A  $^4\text{He}$  superflow corresponds to a number ( $N$ ) of  $^4\text{He}$  atoms flowing together. If this superflow carries zero entropy and heat, that is equivalently to say that the quantum state of the  $N$   $^4\text{He}$  atoms in the superflow is the lowest energy state at given momentum (or at given current value). We know that the time evolution of the whole system (the superflow plus its environment) is governed by the many-body Schrodinger equation. In this time evolution, the quantum state of the environment is a mixed quantum state, corresponding to a certain temperature. The subsystem of the  $N$   $^4\text{He}$  atoms (superflow) can be expected to be a mixed quantum state too. It is hard to imagine how this subsystem could reach a zero entropy and zero thermal energy quantum state following the time evolution. Even if at a moment this superflow reaches this zero entropy quantum state dramatically, it shall evolve into a mixed state at the following moments. In other words, the superflow shall be a thermal flow in a thermal environment, similar to any conventional flows.

Can we understand that a  $^4\text{He}$  superflow is both thermal and superfluidic ( i.e., keeping its current from decay)? A recently developed quantum theory of superfluidity [2, 3, 4] provides an affirmative answer. This microscopic theory shows that the many-body spectrum of a superfluid has a characteristic feature [2, 3, 4]. Consider a superfluid composed of  $N$  particles in a limited geometry, the Hamiltonian of this many-body system can be written as

$$\widehat{H} = -\sum_{i=1}^N \frac{\hbar^2}{2M} \frac{\partial^2}{\partial \mathbf{r}_i^2} + \sum_{i<j}^N V(\mathbf{r}_i - \mathbf{r}_j), \quad (1)$$

where  $M$  is the mass of a particle and  $V(\mathbf{r})$  represents the inter-particle interaction. Consider the eigenspectrum of the Hamiltonian operator, labelled by  $\kappa$ ,

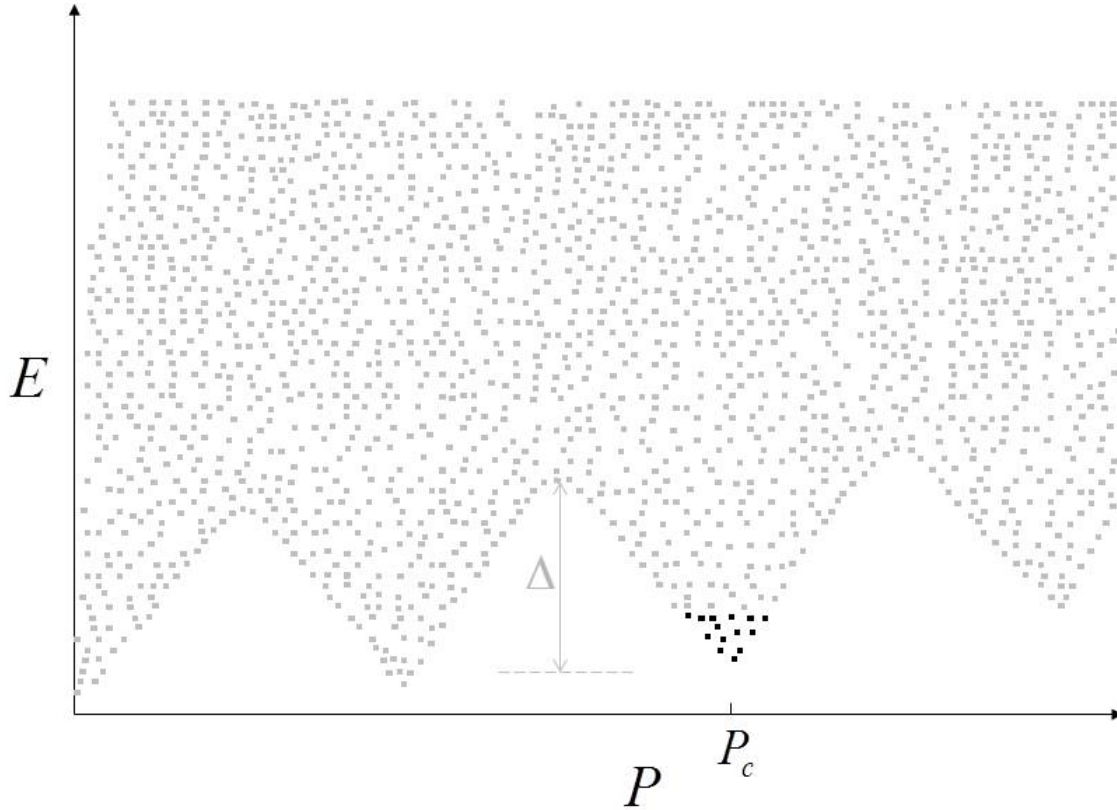
$$\widehat{H}\psi_\kappa(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N) = E_\kappa\psi_\kappa(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N), \quad (2)$$

where  $E_\kappa$  is eigenlevel and  $\psi_\kappa$  is the eigenwavefunction. We shall consider also the momentum carried by eigenwavefunction  $\psi_\kappa$ ,

$$P_\kappa = \langle \psi_\kappa(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N) | \widehat{P} | \psi_\kappa(\mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N) \rangle, \quad (3)$$

where  $\widehat{P}$  is the total momentum operator along a superflow direction.  $\psi_\kappa$  is not required to be an eigenwavefunction to the operator  $\widehat{P}$ .

If one schematically plots the energy levels of this system at the energy-momentum ( $E - P$ ) plane (see Fig. 1), one then sees that the low-lying levels form valley-like structures at the boundary region [2, 3, 4]. The relevant quantum states at low temperature corresponds to those levels within the bottoms of the valleys and one can ignore the levels at higher energies. A superflow state (at low temperature) corresponds to some occupied levels at a valley at a non-zero momentum. The system is not allowed to jump from the occupied levels at this valley to left-side valleys with less momenta, due to the energy barriers which separate the valleys. The prohibition of inter-valley jumps ensures that a superflow keeps its momentum from decay. For a given superflow, the occupation probability distribution at a relevant valley follows a Boltzmann distribution, namely, the occupation probability of a level at the valley is



**Figure 1.** A schematic plot of many-body eigen levels of a superfluid in the  $E - P$  Plane. Dots (in gray and in black) represent levels. The horizontal and vertical coordinates of a dot correspond to the momentum and the energy of the level, respectively.  $\Delta$  denotes the height of an energy barrier between two "valleys". Dots in black are the occupied levels of the system (at low temperature), corresponding to a superflow state with a momentum of  $P_c$ .

proportional to  $e^{-E/kT}$ , where  $E$  is the energy of the level,  $k$  is the Boltzmann constant and  $T$  is the temperature of the superflow. Microscopically this thermal distribution is caused by the quanta exchanges between the superflow and its surroundings, which in turn is caused by microscopic interactions between the atoms in the superflows and the particles (atoms or molecules) in the surroundings.

Once realizing that  $^4\text{He}$  superflows are still thermal flows, one can expect a phenomenon of  $^4\text{He}$  superflows similar to the Peltier effect of electric currents. When a  $^4\text{He}$  superflow passes from a medium to a different medium, it shall experience a temperature change. The heat content ( specific enthalpy) of a superflow in the first medium as a function of temperature differs from the heat content function in the second medium. For the conservation of energy, the temperature of the superflow shall be

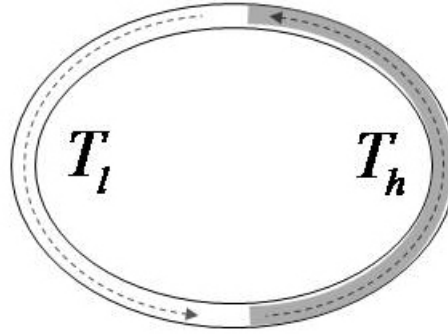


**Figure 2.** The temperature of a  $^4\text{He}$  superflow changes when exiting a medium to a different medium.

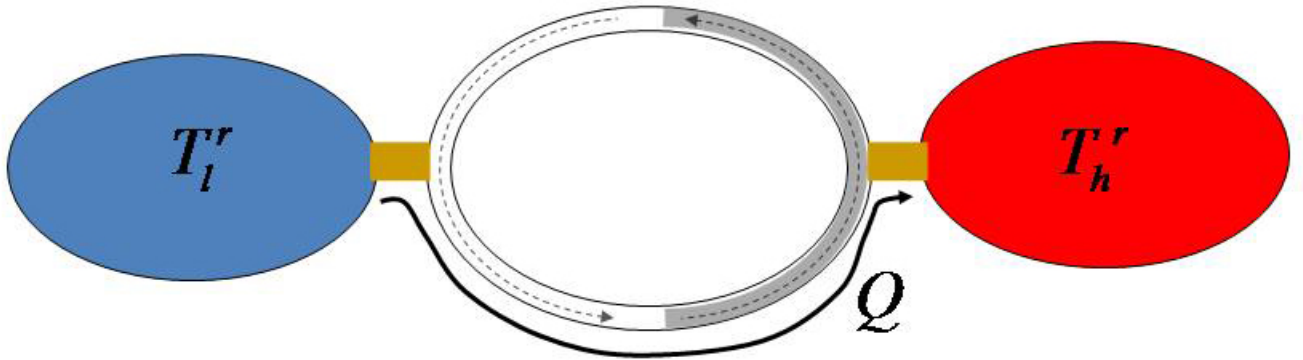
adjusted so that heat content remains the same (roughly) when the superflow exits the first medium (see Fig. 2). In literature, the temperature change of  $^4\text{He}$  superflow exiting a medium to a rather large empty space was reported [5] shortly after the discovery of superfluidity [6].

One could note that the flow velocity of the superflow generally changes when it passes from the first medium to the second medium. If the first medium has a porosity smaller than the second medium, then the flow velocity in the first medium is larger than the flow velocity at the second medium. It can be shown that the heat content of a superflow in a medium depends on the flow velocity [7], which is quite unusual from a classical viewpoint. Qualitatively, the larger the flow velocity, the smaller the heat content. Such a dependence of a superflow's heat content on the flow velocity could make a large contribution to this "Peltier effect" of the superflow.

In [1], we consider a system referred as to a heterogeneous superflow loop (HSL). It is a circling  $^4\text{He}$  superflow filling a torus-shaped vessel, where half of the vessel is packed with one kind of medium and the other half is packed with a different medium [8] (see Fig. 3). one can find an interesting stable temperature configuration along an isolated HSL. The superflow in one medium has a temperature  $T_h$  higher than the temperature of the superflow at the other medium (denoted by  $T_l$ ). With such a temperature difference, the heat content of superflow in one medium is (approximately) the same as the heat content of superflow in the other medium, so that net heat transfer from one medium to the other, caused by the superflow, becomes zero (approximately). To show a dramatical counterexample to SLT, consider to prepare two infinitely large heat baths (besides a HSL), with one bath at a temperature  $T_h^r$  and the other at a temperature  $T_l^r$ .  $T_h^r$  and  $T_l^r$  is set to satisfy  $T_h > T_h^r > T_l^r > T_l$ . Consider making a good thermal contact between the high temperature part of the HSL and the bath at  $T_h^r$ , and making a good thermal contact between the low temperature part of HSL and the bath at  $T_l^r$ . Then, the superflow absorbs some heat from the heat reservoir at  $T^r$ , and this (moving) superflow transfers the heat to the high temperature part of the HSL, and eventually the heat is passed to the heat reservoir at  $T^h$  (see Fig. 4). This is a process in which the entropy of the whole system decreases. The entropy-decreasing process can run for a cosmologically long time, since that the decay of the superflow is prevented by some



**Figure 3.** A heterogeneous superflow loop. The temperature of the superflow in one medium differs from the the temperature of the superflow in the other medium. This temperature difference is induced by the superflow.



**Figure 4.** An exception to SLT. There is a heat flow from the heat reservoir at  $T_l'$  to another heat reservoir at a higher temperature.

energy barriers [9].

In [1], we sketch out a prototype of a system for extracting thermal energy from the environment. This potential energy approach is environmentally friendly to a great extent. The energy-generating process can be purely physical, without consuming any materials or producing any unwanted materials. It can be roughly estimated that a system with one kilogram of liquid helium generates ideally a power of several kilowatts or more, but some relevant cryogenic technology needs to be developed for achieving such an efficiency.

To summarize, a quantum exception to SLT can be constructed with  $^4\text{He}$  superflows. Financial supports from Chinese NSF (Grant No. 11474313), from CAS (Grant

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